EXAMINATION OF LINER STABILITY DURING MAGNETIC IMPLOSION USING EXPERIMENTS AND SIMULATIONS

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Abstract

Los Alamos has been conducting a number experiments to examine dynamic properties of materials using high-energy pulse power generator systems. These experiments are conducted in a Z-pinch configuration typically with an outer aluminum liner to carry the current, develop the acting force, and act as the driving element. The peak magnetic fields produced by these systems have ranged from 0.5 to 1.7 mega gauss. The onset of what has been called Magneto-Raleigh-Taylor (MRT) instabilities in the outer aluminum liner, when excessive current is applied, has been considered a limitation on the design of these liners. However, in several cases where the material of the liner was calculated to be completely melted the outside liner surface remained stable. Analysis of the data from this and several other experiments and comparison to 1D MHD simulations has already permitted us to examine how the drive conditions on this aluminum layer appear to effect the likelihood of onset of these instabilities. Additionally, careful variations of drive conditions, initial liner surface conditions, and EOS properties (including conductivity) suggest two phenomenons that appear to cause onset of instability. First, while the nature of the instability may still be fundamentally driven by the acceleration of a fluid interface, the effect may be drastically accentuated by the onset of liquid to vapor phase change if the material is allowed to approach too closely to the saturated liquid line. Furthermore, several observed cases which remained stable even after melting suggest that there may be drive conditions which maintain the aluminum at densities and temperatures above the saturated liquid line and significantly delay the onset of MRT instabilities. Second, the gradient of distribution of forces within the melted liner may also impact the growth of instabilities. We will also present the results of 2D simulations of these conditions and examine in greater detail the apparent mechanisms by which these instabilities grow.

I. Introduction

More uses are being identified for metal liners at or near solid density driven in a Z-pinch configuration by pulse power sources. [Refs 1,2,3] Applications for these liners include impact or compression drivers for many hydrodynamic experiments. We have refrained from driving solid liners hard enough to melt them and used specific action (in J/kg) required to melt as the design limit for the liner drivers used. But, the ultimate goal in many of these experiments is to achieve higher pressures, temperatures, and energies than this limitation allows. In order to achieve these higher energy densities we must accelerate the liner driver to velocities in excess of 1 cm per microsecond or apply compress ional forces on the order of many mega-bar. This typically results in applying sufficient specific action to melt a large fraction of the mass on the surface of the liner. Melting of the outside of the liner in general is then followed by the rapid growth of surface perturbations akin to that observed in classic Rayleigh-Taylor instabilities. If unconstrained the instability grows enough to destroy the liner.

Table 1 Unstable (U) and Stable (S) Examples

Exper.	Peak Current (MA)	Peak Time (μs)	Peak Magnetic Pressure (Gpa)	Specific Action (A^2s/m^4)
LD-1 (U)	19.7	6	3.15	$1.65x10^{16}$
NTLX (S)	15.8	8	3.0	$2.15\ x10^{16}$
MTF-1 (S)	11.5	8.5	1.3	$1.38\ x10^{16}$
ALT-1 (?)	32	3	23.7	$1.77\ x10^{16}$
LS-9 (M)	10.0	8	11.5	$4.0\ x10^{16}$

The objective of this effort has been to identify key issues defining stability based on analysis and simulations of observed stable and stable liners. We attempted to examine the differences with the desire of relating them back to the drive conditions (e.g. current spatial and temporal profile). Ultimately, we want to develop a set of parametric curves that help in selection of initial conditions for the liners as a function of drive conditions that would guarantee stability for the liner driver for some predictable length of time. The results of this study, while inconclusive at this time, allow us to make several significant observations.

II. Background

Several liner Z-pinch experiments we have conducted produced interesting and contradicting results concerning the stability of the liner driver and the

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUN 2003**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Examination Of Liner Stability During Magnetic Implosion Using Experiments And Simulations**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Plasma Physics Group, Los Alamos National Laboratory, Los Alamos New Mexico 87545**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**		
13. SUPPLEMENTARY NOTES **See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. IEEE International Pulsed Power Conference (19th). Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.**		

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Los Alamos has been conducting a number experiments to examine dynamic properties of materials using high-energy pulse power generator systems. These experiments are conducted in a Z-pinch configuration typically with an outer aluminum liner to carry the current, develop the acting force, and act as the driving element. The peak magnetic fields produced by these systems have ranged from 0.5 to 1.7 mega gauss. The onset of what has been called Magneto-Raleigh-Taylor (MRT) instabilities in the outer aluminum liner, when excessive current is applied, has been considered a limitation on the design of these liners. However, in several cases where the material of the liner was calculated to be completely melted the outside liner surface remained stable. Analysis of the data from this and several other experiments and comparison to 1D MHD simulations has already permitted us to examine how the drive conditions on this aluminum layer appear to effect the likelihood of onset of these instabilities. Additionally, careful variations of drive conditions, initial liner surface conditions, and EOS properties (including conductivity) suggest two phenomenons that appear to cause onset of instability. First, while the nature of the instability may still be fundamentally driven by the acceleration of a fluid interface, the effect may be drastically accentuated by the onset of liquid to vapor phase change if the material is allowed to approach too closely to the saturated liquid line. Furthermore, several observed cases which remained stable even after melting suggest that there may be drive conditions which maintain the aluminum at densities and temperatures above the saturated liquid line and significantly delay the onset of MRT instabilities. Second, the gradient of distribution of forces within the melted liner may also impact the growth of instabilities. We will also present the results of 2D simulations of these conditions and examine in greater detail the apparent mechanisms by which these instabilities grow.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**4**	

relative drive conditions. Specifically, the NTLX experiments conducted at Shiva Star and the LD series of experiments at Atlas were nominally designed to achieve the identical liner velocity using the same specific action. The surprise was that the NTLX liner was observed experimentally to be stable, but the LD liner was clearly unstable. This result prompted the review of a number of experiments and their post-shot analysis to examine possible dependence of stability on drive parameters. This review included experiments driven by Pegasus (a predecessor of Atlas), explosive pulse power generators, Atlas, and Shiva Star. The comparison of drive parameters is shown in Table I. With the exception of ALT-1 the assessment of stability is based on radiography images from each of the experiments, examples of which are shown in Figure 1.

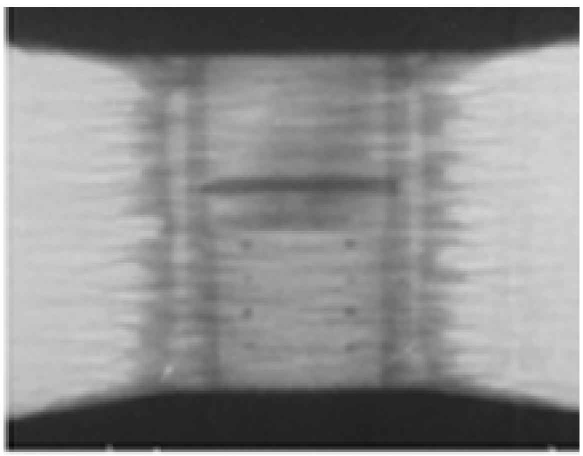

Figure 1a. Unstable Example (LD-1)

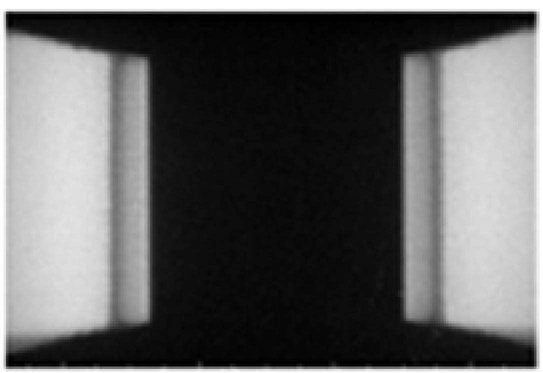

Figure 1b. Stable Example (NTLX)

Figure 1 Unstable (a) and Stable (b) Liners

Since the liner for the two experimental series NTLX and LD, shown in Figure 1, were so similar in drive conditions, yet the resulting conditions of the liner were so drastically different, we felt these two cases made an excellent set to use in the initial analysis. Pre-shot calculations had been conducted for these two experiments and the results of those simulations predicted stability for both liners. The same liner design was used in the NTLX series 5 times with no significantly observable instability. This fact and the pre-shot simulations led us to believe the LD liner would be stable, since less specific action was applied to the liner and the LD liner was 20% more massive. In fact, a smaller fraction of the mass was predicted to melt in the LD liner than in the NTLX case. However, as seen in Figure 1, radiography in the LD experiments showed the liner was grossly unstable.

III. Simulations Technique

With these experiments as test cases, the next step was to use 1D and 2D MHD simulation codes to estimate the thermodynamic and hydrodynamic conditions in the liner. We used a 1D Lagrangian and 2D Eulerian AMR treatment. In both simulations the measured current was applied as a boundary condition to the calculations. For the 2D simulations the outside surface features were measured using high precision laser metrology. This data specified the physical structure on the outer surface. While the mesh size of the 2D simulations was on the order of 80 x 80 microns, the metrology data was accurate to better than 1 micron. Simulation of these features in the 2D simulation relied on a "mixed cell" treatment, which tracks the volume faction of differing materials and the properties and state conditions of each material. The simulations also used an interface reconstruction algorithm to track the growth until the surface features become large enough to be resolved by the mesh.

IV. Results

The first question was why did the initial 2D simulations not predict the instability of the LD liner design. This question was first addressed by extensive parametric variations of the input parameters for the liner and the drive conditions. For example, assuming uncertainty in measurements of the surface structure on the outer surface of the liner, varying the initial amplitude of the surface structure would test the sensitivity of the simulation to this factor. We discovered that an increase by a factor of 20 in amplitude was required to achieve growth on the surface comparable to what was observed in the radiograms. This dismisses errors based on relative surface roughness as an explanation. Also considered were input conditions such as current drive, liner thickness, bulk electrical conductivity, equation of state (EOS), and several others.

The EOS data used for these simulations were the SESAME tabular library [Ref. 4]. This database is compiled from both theoretical models and measured

data. There are multiple tables for aluminum. While subtle variations in these Aluminum tables do exist, the basic form is very similar. Three tables (i.e. 3715, 3717, and 3719) have predicted the bulk behavior of the liners in previous experiments well. Which table is best has until now been a personal preference. In this analysis we tested the ability of each of these tables to properly reproduce the results in two experiments. The calculations indicated that only the 3719 SESAME table adequately predicted the onset and relative level of growth of the instabilities.

While phase change information is not explicitly provided in these tables, the location of the vapor dome can be located by the inflection in isotherms as they pass through the saturated vapor line and the saturated liquid line. Using this condition to locate the onset of phase change in the different tables and examine the implied location of the saturated liquid line, it becomes obvious that the inferred 3719 saturated liquid line is located much closer to the initial conditions. This has an implication regarding the path in phase space the aluminum in the outer layers follows in phase space during the heating and pressurization of the aluminum.

It is possible to compare the trajectories in phase space for both the unstable LD liners and the stable NTLX liners as calculated in the simulation using the 3719 EOS table. The phase space path followed by the material is a result of both material pressure and magnetic forces. The pressure/temperature relationship determines the potential to have the material expand as a consequence of heating. The dependence of conductivity on temperature and density causes any material that expands to become more resistive and the magnetic field becomes less effective as a piston.

The aluminum begins at a temperature of 0.025 eV and a density of 2.7 g/cm^3 and low resistivity (~2.5 μohm-cm). The corresponding pressure for this condition is approximately 1 Bar. As current is applied, the temperature increases and the density drops slightly. Examination of the phase space trajectories indicates this heating occurs at nearly constant pressure and hence it follows a path just skirting the saturated liquid line. This nearly constant pressure condition is maintained during the inward acceleration of the liner. Magnetic diffusion results in a non-uniform current density distribution producing slight differences in heating and slightly different temperatures at different depths in the liner. This spreading of the temperature continues until collision.

Comparing the phase space "trajectories" of the stable NTLX liner with the unstable LD-1 liner shows a subtle but important difference. The spread in distribution of temperatures and densities of the layers in the unstable LD-1 liner is much larger than that of the stable NTLX liner. This spread causes the outer layer of the unstable LD-1 liner to reach a higher temperature and lower density than in the NTLX liner. The conductivity of the outer surface of the LD-1 liner drops fairly quickly two and a half orders of magnitude below that predicted on the outer surface of the NTLX liner. This reduction in conductivity reduces the effectiveness of the magnetic field to keep the material compressed. Once the material begins to expand the conductivity drops even more. The lower conductivity also means the material is heated less. Thus the material is not heated quick enough to reach the higher conductivities in the region above 1eV. This results in a run-away condition. Thus the simulation predicts the outer surface of the LD-1 liner will undergo a relatively violent phase change. The onset of this rapid phase change is very sensitive to pressure and density variations on the surface.

Using the now preferred EOS table 3719 and 2D simulations, we recalculated the conditions for the entire family of liner experiments we have conducted in the past for which we have radiographic data. Comparison of the simulations with the data showed excellent agreement and lends validity to the use of this EOS to

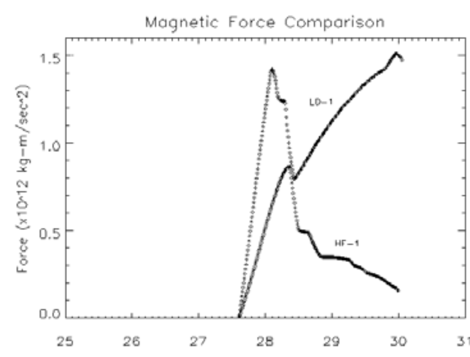

Figure 2 Comparison of stable (HF-1) and unstable (LD-1) force distribution

properly simulate the onset of instability.

Next it is important to examine the evolution of the force per unit mass as a function of depth in the liner as predicted by simulations. Figure 2 is a comparison of the calculated magnetic force (j x B) as a function of radius in the liner for LD-1 (the upper curve) and HF-1 (the lower curve). These profiles are established after each liner has traveled about 20 mm. Each point represents the force on a Lagrangian cell. For both cases starting at the inside surface of the liner the magnitude of the magnetic force increases to a peak value. This region is solid and has a relatively constant density and temperature, hence nearly constant conductivity and strength. After the peak force and further out in radius the magnetic force is predicted to become smaller as the materials temperature is increasing and the conductivity drops. At some point the materials temperature reaches melting. In the case of the LD-1 profile this corresponds to where the magnetic force reaches a minimum. For

HF-1 the melt interface is located at the second inflection. At this point the difference between the stable and unstable behavior is illustrated. For the unstable LD-1 liner the magnetic force increases with radius while the opposite is true for the stable HF-1 liner. The premise presented here is that a positive gradient in the acting force opposite to the direction of motion in a fluid is inherently hydro-dynamically unstable. This is the case for the calculated results of the LD-1 simulation. While these calculation are 1D and do not allow for variations in the z direction, even the slightest variation in density or force in the z direction, as with any real surface finish, would set up 2d shear flow and allow for the interchange of outer material with inner material.

V. Conclusions

Based on the assumption that the gradient of the force is a test of the stability of the melted layer on the outer surface of the liner, it is possible to develop a design curve for a pulse power source. Our simulations suggest it does not appear possible to obtain an initial stable profile when the liner first starts to melt if the driving waveform is a damped sinusoid (e.g. Switched Marx Bank). However, the right selection of voltage and total mass of the liner (i.e. liner thickness) allows the force profile to relax to a stable profile quickly.

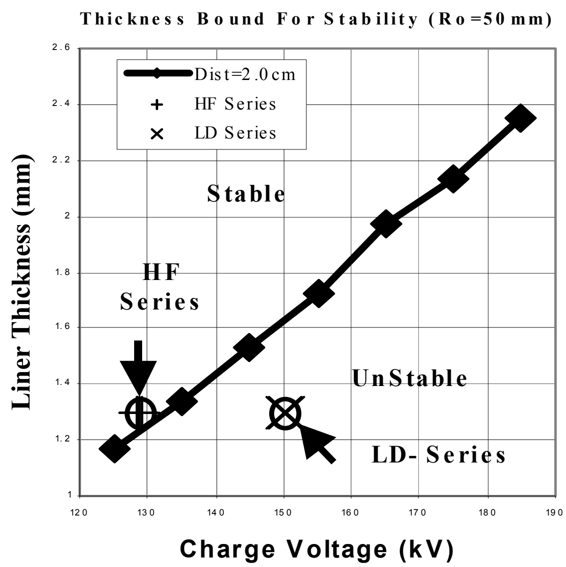

Figure 3 Proposed Atlas stability threshold curve

Using this concept we can use the 1D simulations for a specific pulse power drive to generate a hypothetical stability threshold curve as a function of liner thickness and bank charge voltage. This curve is very dependent on wave shape of the driving current because of the temporal effects of diffusion and heating. Figure 3 is the resulting curve. This curve is calculated for an ATLAS waveform and a starting outer radius of 50 mm. Also shown on the curve are results of the LD and HF series of experiments, which fall on the proper side of the hypothetical stability threshold.

V. References

1. R.K. Keinigs W.L. Atchison, W.E. Anderson, etal., “Material Science Experiments on the Atlas Facility”, Digest of Technical Papers, Pulsed Power Plasma Science 2001,
Eds. Robert Reinovsky and Mark Newton, IEEE Catalog Number 01CH37251, pp. 356-60.

2. R. E. Reinovsky, “Pulsed Power Experiments in Hydrodynamics and Materials Properties” Digest of Technical Papers 12th IEEE International Pulsed Power Conference, Eds. C. Stallings and H. Kirbie, IEEE Catalog Number 99CH36358, pp. 38-43.

3. I.R. Lindemuth and R.C. Kirkpatrick, “Parameter Space for Magnetized Fuel Targets in Inertial Confinement Fusion”, Nuclear Fusion **23,** 263(1983).

4. J. D. Johnson “SESAME Data Base”, National Technical Information Service Document, No. DE94-011699.